

Search for High-Mass States with Lepton Plus Missing Transverse Energy Using the ATLAS Detector at Center-of-Mass Energy of 7 TeV

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The ATLAS detector has been used to search for high-mass states decaying into a single high momentum lepton and missing transverse energy, such as new heavy charged gauge bosons. The latest search results for a W' boson decaying to lepton plus neutrino in 1.04 fb^{-1} of proton-proton collisions at a center of mass energy of 7 TeV produced at the Large Hadron Collider are presented.

1. Introduction

In March of 2011 the Large Hadron Collider (LHC) had begun, once again, colliding protons at a center-of-mass energy of 7 TeV. By June the ATLAS detector had recorded more than 1 fb^{-1} of proton-proton collisions¹. These proceedings summarize the search for a W' boson decaying to a lepton (where lepton is defined as a muon or electron) plus a neutrino using 1.04 fb^{-1} of data collected by the ATLAS detector [1].

There are many extensions to the Standard Model (SM) of particle physics that predict a new high-mass state similar to the W boson in the SM [2, 3]. The sequential, standard model (SSM) boson, i.e. the extended gauge boson of Ref. [3], is used to model a W' boson with the same couplings to leptons as the SM W boson but at a higher mass.

No W' boson signal is observed, and the data is used to set new limits [4] on σB (cross section times branching fraction) as a function of the W' boson mass. Table I shows the signal production cross sections used for each mass point. The search is performed in the individual electron and muon channels where limits on $W' \rightarrow e\nu$ and $W' \rightarrow \mu\nu$ are set. The channels are also combined assuming the same branching fraction for both channels. The limits are determined by examining the transverse mass (m_T) distribution for resonant states above 500 GeV, where m_T is constructed from events with a single high transverse momentum (p_T) lepton plus large missing transverse energy (E_T^{miss}),

$$m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu})}. \quad (1)$$

Here $\phi_{\ell\nu}$ is the angle between the lepton p_T and E_T^{miss} vectors².

A bayesian method is used to search for an excess of the m_T signal above the expected backgrounds. When no excess is observed (above 3σ) a limit on the cross section (σ_{SSM} significance) times branching ratio (BR) is set where the SSM W' boson is used as a benchmark for setting limits.

These proceedings begin with a brief description of the ATLAS detector in section 2, followed by an explanation of the event selection in section 3. The explanation of the modeling of the backgrounds is done in section 4. Section 5 presents the final results and these proceedings are concluded in Section 6.

2. Description of the ATLAS Detector

The ATLAS detector is a general purpose particle detector that is characterized by three different components, the inner-detector (ID), the calorimeter, and the muon system (MS). The innermost system is the inner-detector which consists of a silicon pixel detector and a silicon strip detector covering $|\eta| < 2.5$. A transition radiation tracker is the outer tracker of the ID and covers $|\eta| < 2.0$. The ID is immersed in a homogenous 2 T field produced from a superconducting solenoid. The ID allows reconstruction of the vertices and tracks of charged particles

¹The uncertainty assigned to the luminosity measurement for all channels is 3.7%.

²The nominal interaction point is defined as the origin of the coordinate system, while the anti-clockwise beam direction defines the z -axis and the $x - y$ plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the center of the LHC ring and the positive y -axis is defined as pointing upwards. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$. The distance ΔR in $\eta - \phi$ space is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

originating from the interaction region. A finely segmented, hermetic calorimeter system surrounds the ID and covers $|\eta| < 4.9$ as well as provides three-dimensional reconstruction of particle showers. The electromagnetic (EM) calorimeter uses liquid argon, while the outer calorimeter, which primarily detects hadronic showers, uses scintillating tiles in the barrel ($|\eta| < 1.7$) and liquid argon for higher $|\eta|$. The energy resolution for an electron approaches 1% for electrons above 50 GeV in E_T . The MS, situated outside the calorimeters, is immersed in a ≈ 1.4 T toroidal field that is produced by superconducting air-core toroids. The integral magnetic field for the MS is about 3 Tm on average. The curvature of the muons as they pass through the magnetic field is measured with three layers of precision drift-tube chambers in the region $|\eta| < 2.0$ and one layer of cathode-strip chambers followed by two layers of drift-tube chambers for $2.0 < |\eta| < 2.7$. Resistive-plate and thin-gap chambers provide the triggering for muons and measure the ϕ coordinate. The muon system is able to achieve a momentum resolution of $\approx 15\%$ at 1 TeV.

3. Event Selection

The event selection for this analysis first requires that all events were recorded while the detector was operating in an optimal fashion. A well reconstructed primary vertex, with at least three reconstructed tracks associated with the vertex is required to be present in the event (all objects selected in the event are then required to be associated with this primary vertex). The primary vertex is also required to be reconstructed within 200 mm, along the z -axis, of the center of the interaction region. Events are then examined to determine if any jets have abnormal shapes. If an event has a poorly reconstructed jet, then it is thrown out as this type of event could bias the E_T^{miss} measurement. Only events that fire specific single-lepton triggers are included in the search. For the electron channel the lowest unprescaled lepton trigger for the dataset has a 22 GeV E_T threshold. The trigger requires an EM cluster in the EM calorimeter that has an energy deposition profile consistent with that of an electron. The trigger also requires that the EM cluster be matched to a track in the inner detector. The muon trigger has to be fired by the RPC or the TGC systems, and to pass a p_T threshold of 20 GeV. Then the trigger object has to match an inner detector track.

In the electron channel, the reconstructed electron energy must be larger than 25 GeV and the electron must have an $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The offline energy cluster must have an energy deposit that is consistent with that of an electron and is matched to an offline track. The offline track is required to have a transverse impact parameter within 0.1 cm of the primary vertex and a longitudinal distance from the primary vertex within 1.0 cm. A hit from the first layer of the pixel detector is required to be associated with the electron track. Finally the energy isolation of the electron, $\Sigma E_{T\text{Calo}}(R < 0.4)$ is required to be less than 9 GeV. Events with an additional electron are vetoed.

The muon channel makes the following offline requirements. The offline muon track is first matched to the trigger object. A p_T cut of 25 GeV is then required, where the p_T is the combined transverse momentum in the MS and the ID. The $|\eta|$ of the muon must be less than 1.0 or $1.3 < |\eta| < 2.0$. The combined track of the muon is required to have a transverse impact parameter less than 0.1 cm from the primary vertex and a longitudinal distance from the primary vertex less than 1.0 cm. The muon track in the MS is required to register hits in all three stations of the MS, ensuring the best possible momentum measurement. As an additional quality cut, the significance of the difference of the curvature measurements between the ID and the MS is required to be less than 5σ . This requirement ensures that no poorly measured muons pass into the final sample. The track isolation, $\Sigma p_T(\text{ID tracks } R < 0.3)$, is to be less than 5% of the muon's p_T . Events with additional muons are also vetoed.

Finally both channels are required to have E_T^{miss} greater than 25 GeV. In order to further reduce the amount of background from light flavor or heavy flavor decays in the electron channel, the E_T^{miss} is required to be larger than 60% of the electron E_T . The final distributions of the lepton p_T and E_T^{miss} are shown in Figs. 1 and 2. These figures also show several mass point distributions of SSM W' boson MC signal. The SSM W' boson production MC has been generated using PYTHIA and corrected for NNLO QCD corrections.

4. Background Modeling

The largest contribution to the background is the SM W and Z boson production. The SM W boson is an irreducible background and is modeled using PYTHIA to generate the background events at LO with the shape of the m_T distribution then corrected to NNLO. The Z boson production becomes a contribution when one of the leptons from the leptonic decay is not reconstructed and then mimics real E_T^{miss} . This contribution is reduced by requiring an additional lepton veto in the event, and is modeled in the simulation.

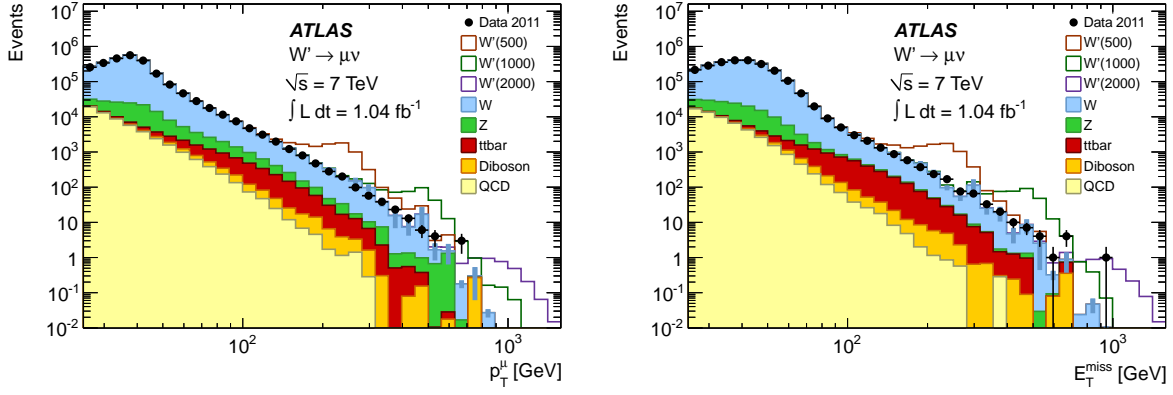


Figure 1: Lepton p_T (left) and E_T^{miss} (right) spectra of the muon channel after event selection. The points represent data and the filled histograms show the stacked backgrounds. Open histograms are $W' \rightarrow \mu\nu$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD backgrounds estimated from data are also shown. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (approximate-NNLO for $t\bar{t}$) cross sections listed in Table I .

Table I: Calculated values of σB for $W' \rightarrow \ell\nu$ and the leading backgrounds. The value for $t\bar{t} \rightarrow \ell X$ includes all final states with at least one lepton (e, μ or τ). The other processes are exclusive and are used for both $\ell = e$ and $\ell = \mu$. All calculations are NNLO except $t\bar{t}$ which is approximate-NNLO.

Process	Mass [GeV]	σB [pb]
$W' \rightarrow \ell\nu$	500	17.25
	600	8.27
	750	3.20
	1000	0.837
	1250	0.261
	1500	0.0887
	1750	0.0325
	2000	0.0126
	2250	0.00526
	2500	0.00234
$W \rightarrow \ell\nu$		10460
$Z/\gamma^* \rightarrow \ell\ell$ ($m_{Z/\gamma^*} > 60$ GeV)		989
$t\bar{t} \rightarrow \ell X$		89.4

The next largest contributions to the backgrounds are SM diboson and $t\bar{t}$ production. These events also have real leptons and E_T^{miss} and are modeled using simulated events. The $t\bar{t}$ production is corrected to approximate-NNLO [5–7]. The production cross sections used are given in Tab. I.

The last significant contribution to the backgrounds are events where a hadron, or photon, will mimic an electron or produce a muon in the course of the decay of the hadron. These types of events, when produced with sufficient E_T^{miss} will pass the selection cuts of the analysis. Such background events are collectively referred to as QCD production. This contribution ends up being negligible as it is very rare for an isolated muon to be produced from a hadronic decay. To model this contribution to the electron channel, an ABCD method was used [8], where the discriminating variables used were E_T^{miss} and the electron isolation. The fraction of isolated electrons was determined in the low E_T^{miss} region and extrapolated to the high E_T^{miss} region. Table II shows the contributions of the backgrounds for a particular mass point.

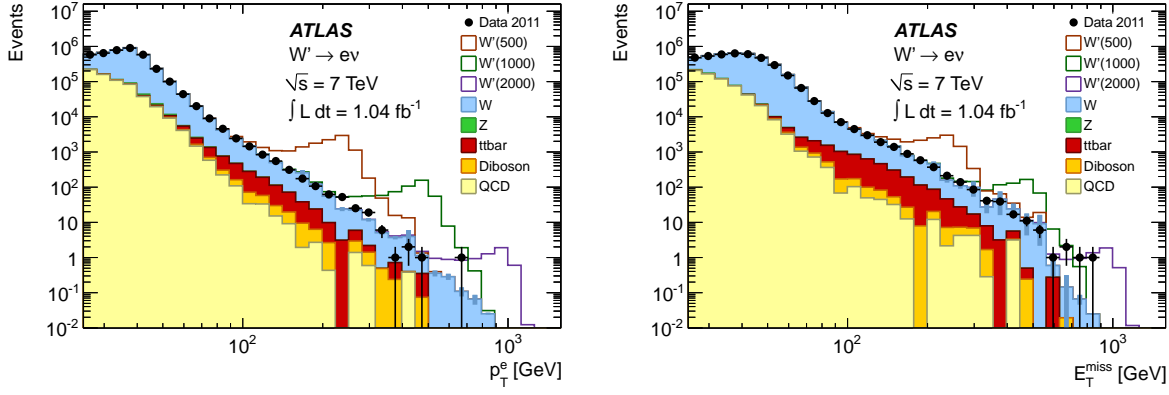


Figure 2: Lepton p_T (left) and E_T^{miss} (right) spectra of the electron channel after event selection. The points represent data and the filled histograms show the stacked backgrounds. Open histograms are $W' \rightarrow e\nu$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD backgrounds estimated from data are also shown. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (approximate-NNLO for $t\bar{t}$) cross sections listed in Table I.

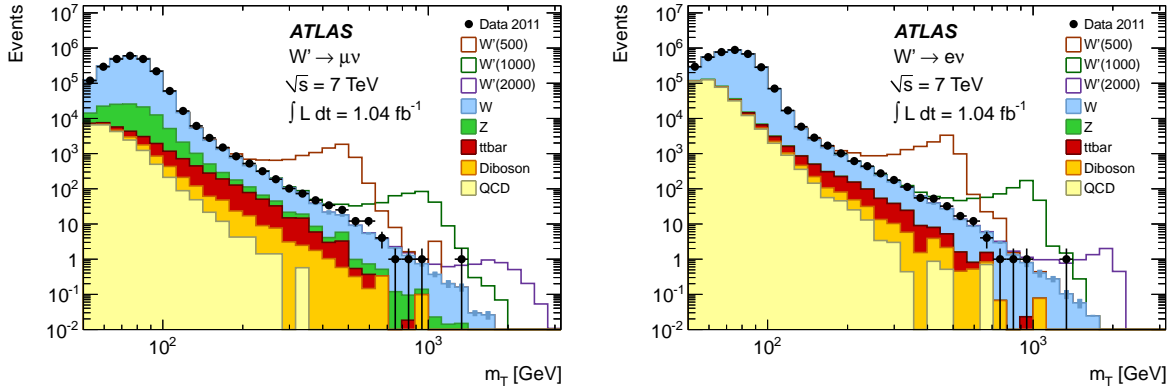


Figure 3: Event m_T spectra of the muon (left) and electron (right) channels after event selection. The points represent data and the filled histograms show the stacked backgrounds. Open histograms are $W' \rightarrow l\nu$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD backgrounds estimated from data are also shown. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (approximate-NNLO for $t\bar{t}$) cross sections listed in Table I.

5. Results

To determine the significance of excess data of any events above the minimum m_T ($m_{T \min}$), a bayesian method is used. The $m_{T \min}$ is determined by minimizing the expected limit on σB in a given mass bin. First a likelihood is constructed from the expected number of events, N_{exp} , where,

$$N_{\text{exp}} = \epsilon_{\text{sig}} L_{\text{int}} \sigma B + N_{\text{bg}}. \quad (2)$$

Here, ϵ_{sig} is the signal efficiency, L_{int} is the integrated luminosity, σB is the signal production cross section times branching ratio, and N_{bg} is the number of background events. The Poisson statistics likelihood, \mathcal{L} to observe N_{obs} events is

$$\mathcal{L}(N_{\text{obs}}|\sigma B) = \frac{(\epsilon_{\text{sig}} L_{\text{int}} \sigma B + N_{\text{bg}})^{N_{\text{obs}}} e^{-(\epsilon_{\text{sig}} L_{\text{int}} \sigma B + N_{\text{bg}})}}{N_{\text{obs}}!}. \quad (3)$$

Systematic uncertainties are treated as Gaussian nuisance parameters, θ_i , in the likelihood,

$$\mathcal{L}(N_{\text{obs}}|\sigma B, \theta_i) = \int \mathcal{L}(N_{\text{obs}}|\sigma B) \prod g_i(\theta_i) d\theta_i, \quad (4)$$

Table II: Expected numbers of events from the various background sources in each decay channel for $m_T > 891$ GeV, the region used to search for a W' boson with a mass of 1500 GeV. The $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ entries include the expected contributions from the τ -lepton. No muon events are found in the $t\bar{t}$ sample above this M_T threshold. The uncertainties are statistical. The final two rows shows the number of expected signal events (N_{sig}) and the number of observed events (N_{obs}) in each channel. The uncertainties on N_{sig} include systematic uncertainties except that of the luminosity.

	$e\nu$		$\mu\nu$	
$W \rightarrow \ell\nu$	1.59	± 0.13	1.36	± 0.13
$Z \rightarrow \ell\ell$	0.00010 ± 0.00004		0.095 ± 0.005	
diboson	0.08	± 0.08	0.11	± 0.08
$t\bar{t}$	0.08	± 0.08	0	
QCD	0	$^{+0.17}_{-0}$	0.01	$^{+0.02}_{-0.01}$
Total	1.75	$^{+0.24}_{-0.18}$	1.57	± 0.15
N_{sig}	49.6 ± 6.0		34.4 ± 4.4	
N_{obs}	2		2	

where $g_i(\theta_i)$ is a probability density function (pdf) for a given nuisance parameter. The main contributions to the nuisance parameters arise from L_{int} , ϵ_{sig} , and N_{bg} . These values are given in Table III. The correlations between the nuisance parameters are neglected given their small effect on the limits.

Table III: Relative uncertainties on the event selection efficiency and background level for a W' boson with a mass of 1500 GeV. The efficiency uncertainties include contributions from trigger, reconstruction and event selection. The cross section uncertainty for ϵ_{sig} is that assigned to the acceptance correction due to the differences in the acceptance from the LO generator and the NNLO. These uncertainties vary from 7% at a 500 GeV W' mass to 10% at a 2500 GeV mass. The last row gives the total uncertainties.

Source	ϵ_{sig}		N_{bg}	
	$e\nu$	$\mu\nu$	$e\nu$	$\mu\nu$
Efficiency	2.7%	3.9%	2.7%	3.8%
Energy/momentum resolution	0.3%	2.3%	2.9%	0.6%
Energy/momentum scale	0.5%	1.3%	5.2%	3.0%
QCD background	-	-	10.0%	1.3%
Monte Carlo statistics	2.5%	3.1%	9.4%	9.9%
Cross section (shape/level)	3.0%	3.0%	9.5%	9.5%
All	4.7%	6.3%	18%	15%

Using this likelihood a posterior probability, $P_{\text{post}}(\sigma B)$, is constructed

$$P_{\text{post}}(\sigma B) = N\mathcal{L}(\sigma B)P_{\text{prior}}(\sigma B), \quad (5)$$

where $P_{\text{prior}}(\sigma B)$ is the canonical flat prior probability, and N is a normalization factor so that the integrated probability is equal to one. The posterior probability is evaluated for each mass and each decay channel as well as their combinations. Then the posterior probabilities are used to assess the discovery significance and set a limit on σB . No excess above 3σ significance is observed, so 95% confidence level (CL) limits on σB are set. The inputs to the likelihood are shown in Tab. IV. Table V shows the upper limits on $W' \rightarrow \ell\nu$ σB for the individual channels and different mass points.

The limits on the individual channels are shown in Fig. 4. The W' boson production is excluded at the 95%, shown in Fig. 5, for masses upto 2.15 TeV. Table VI summarizes the lower limits on σB . The ratio on the lower limit σ for W' boson production to the SSM production cross section versus $M_{W'}$ is shown in Fig. 5.

Table IV: Inputs for the $W' \rightarrow e\nu$ and $W' \rightarrow \mu\nu$ σB limit calculations. The first three columns are the W' boson mass, m_T threshold and decay channel. The next two are the signal selection efficiency, ϵ_{sig} , and the prediction for the number of signal events, N_{sig} , obtained with this efficiency. The last two columns are the expected number of background events, N_{bg} , and the number of events observed in data, N_{obs} . The uncertainties on N_{sig} and N_{bg} include contributions from the uncertainties on the cross sections but not from the integrated luminosity.

$m_{W'}$ [GeV]	$m_{T\text{min}}$ [GeV]		ϵ_{sig}	N_{sig}	N_{bg}	N_{obs}
500	398	$e\nu$	0.388 ± 0.019	6930 \pm 620	101.9 \pm 10.8	121
500	398	$\mu\nu$	0.252 ± 0.015	4500 \pm 430	63.7 \pm 6.5	91
600	447	$e\nu$	0.456 ± 0.022	3910 \pm 330	62.1 \pm 7.1	69
600	447	$\mu\nu$	0.286 ± 0.016	2450 \pm 220	41.8 \pm 4.7	57
750	562	$e\nu$	0.429 ± 0.020	1420 \pm 110	20.7 \pm 3.7	20
750	562	$\mu\nu$	0.293 ± 0.017	970 \pm 79	14.3 \pm 1.4	20
1000	708	$e\nu$	0.482 ± 0.022	417 \pm 35	6.13 \pm 0.92	4
1000	708	$\mu\nu$	0.326 ± 0.019	282 \pm 26	4.98 \pm 0.54	4
1250	794	$e\nu$	0.527 ± 0.024	143 \pm 14	3.09 \pm 0.49	3
1250	794	$\mu\nu$	0.367 ± 0.021	99 \pm 10	2.87 \pm 0.34	3
1500	891	$e\nu$	0.541 ± 0.026	49.6 \pm 6.0	1.75 \pm 0.32	2
1500	891	$\mu\nu$	0.374 ± 0.024	34.4 \pm 4.4	1.57 \pm 0.23	2
1750	1000	$e\nu$	0.515 ± 0.024	17.3 \pm 2.4	0.89 \pm 0.20	1
1750	1000	$\mu\nu$	0.338 ± 0.020	11.4 \pm 1.7	0.82 \pm 0.14	1
2000	1122	$e\nu$	0.472 ± 0.023	6.16 \pm 0.99	0.48 \pm 0.10	1
2000	1122	$\mu\nu$	0.323 ± 0.021	4.21 \pm 0.70	0.44 \pm 0.09	1
2250	1122	$e\nu$	0.415 ± 0.019	2.84 \pm 0.50	0.48 \pm 0.10	1
2250	1122	$\mu\nu$	0.288 ± 0.018	1.97 \pm 0.36	0.44 \pm 0.09	1
2500	1122	$e\nu$	0.333 ± 0.018	0.81 \pm 0.16	0.48 \pm 0.10	1
2500	1122	$\mu\nu$	0.221 ± 0.017	0.53 \pm 0.11	0.44 \pm 0.09	1

6. Conclusion

Using 1.04 fb^{-1} of proton-proton collisions collected at the LHC, ATLAS has searched for a massive boson decaying to a lepton plus missing transverse energy with $m_T > 500 \text{ GeV}$. No significant excess has been observed, so lower 95% CL limits have been evaluated on the production cross section of a SSM W' boson. This analysis has been submitted to Physics Review Letters B [1].

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Table V: Upper limits on $W' \rightarrow \ell\nu \sigma B$. The first column is the mass bin and the following columns are the 95% CL limits of the electron channel, the muon channel, and the combined limit respectively. The limits include all of the systematics as described in the text.

$m_{W'}$ [GeV]	95% CL limit on σB [fb]		
	$e\nu$	$\mu\nu$	both
500	121	191	130
600	61	110	65
750	28.5	51.7	28.1
1000	10.6	16.7	7.7
1250	10.1	14.7	7.5
1500	9.0	13.3	6.7
1750	7.9	12.2	5.7
2000	9.1	13.4	6.7
2250	10.3	15.0	7.6
2500	12.9	19.7	9.6

Table VI: Lower limits on the SSM W' boson mass. Rows correspond to the different decay channels ($e\nu$, $\mu\nu$ or both combined) and the columns give the expected (Exp.) and observed (Obs.) mass limits.

	$m_{W'}$ [TeV]	
	Exp.	Obs.
$e\nu$	2.17	2.08
$\mu\nu$	2.08	1.98
both	2.23	2.15

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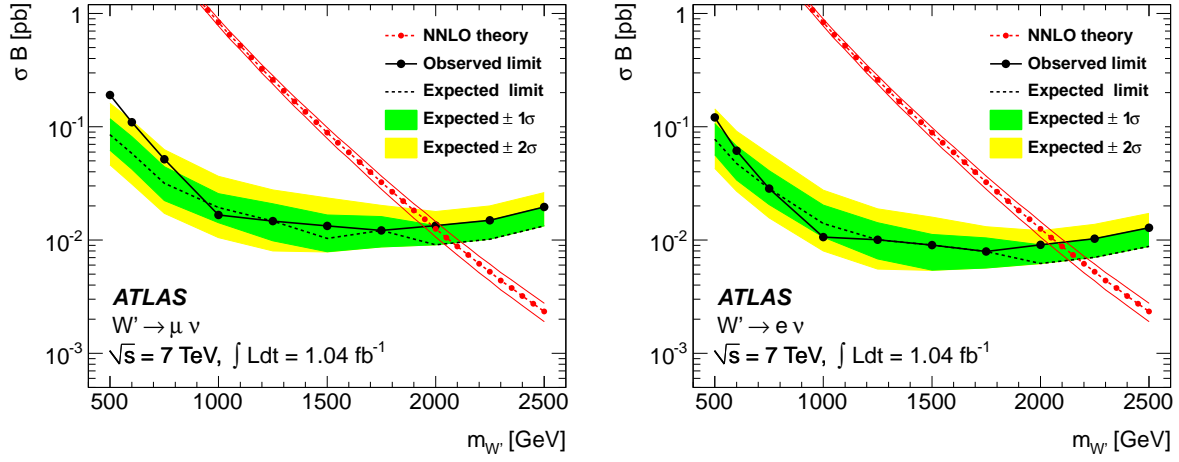


Figure 4: Expected and observed limits on σB for $W' \rightarrow \mu\nu$ (left) and $W' \rightarrow e\nu$ (right). The NNLO cross section for a SSM W' boson and its uncertainty are also shown.

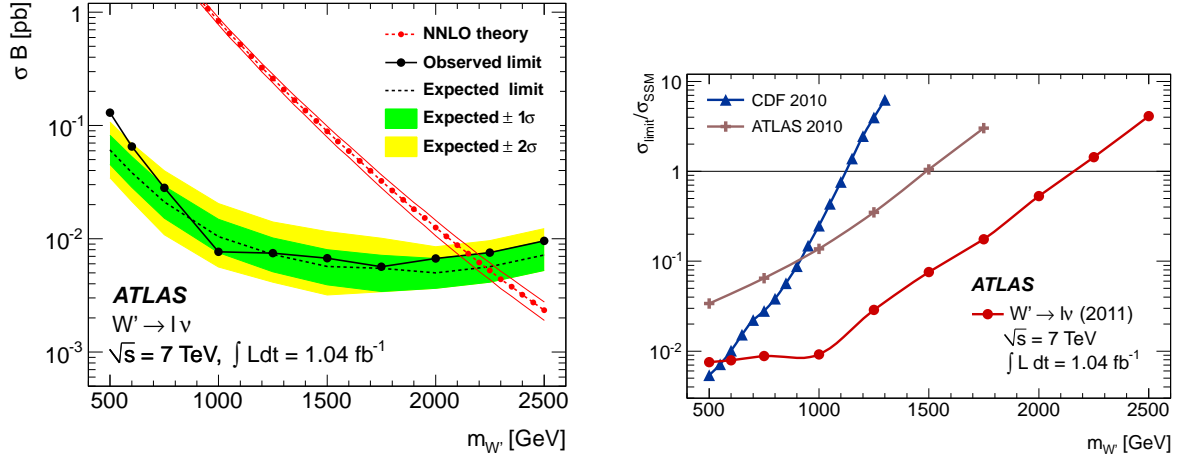


Figure 5: On the left are the expected and observed limits on σB for the combined $W' \rightarrow \ell\nu$ ($\ell = e, \mu$ channels) assuming the same branching fraction for both channels. The NNLO cross section and its uncertainty are also shown. On the right are the normalized cross section limits ($\sigma_{\text{limit}}/\sigma_{\text{SSM}}$) for $W' \rightarrow \ell\nu$ as a function of mass for this measurement and from CDF [9], as well as the previous ATLAS search [4]. The cross section calculations assume the W' boson has the same couplings as the SM W boson. The region above each curve is excluded at 95% CL.